Performance Evaluation of Five New Adaptive Contention Slot Allocators for IEEE 802.16 Based Systems[1]

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***Abstract*— A reservation based Medium Access Control (MAC) protocol has been adopted by the IEEE 802.16 standard as the basic protocol for data communication within the upstream channel. In this paper, we propose the following five new Contention Slot Allocators (CSA) for the IEEE 802.16 MAC protocol: Forced-CSA, Variable-CSA, Multicast-CSA, Collision Free-CSA and CDMA-CSA. The new techniques dynamically fit the number of contention slots needed to solve collisions according to the current traffic load, considerably improving overall system performance. The CSAs introduced in this paper indicate that the mean access delay could be reduced up to 75% compared with the currently adopted method by the IEEE 802.16 MAC Protocol, called Simple-CSA. A performance evaluation of our five CSA schemes is presented and compared with previous CSA schemes, Simple-CSA and IEEE 802.14-CSA. Obtained results turned out to be closer to the maximum estimated throughput than currently used methods.**

***Index Terms*— IEEE 802.16 Performance Analysis, Contention Slot Allocators, Contention Resolution**

I. INTRODUCTION

Broadband Wireless Access (BWA) Networks, which are based on the standard IEEE 802.16, have become the best way to meet residential and small business demand for high speed Internet, multimedia and voice services. This standard adopts the binary truncated exponential backoff algorithm (EBA) with adjustable contention window size to solve collisions of *bandwidth requests* (REQ). The IEEE 802.16 MAC protocol establishes that bandwidth assigned for the uplink channel is mainly conformed by two regions: contention and reservation. The former is used by subscriber stations (SS) to transmit REQ to the Base Station (BS). The latter is used to transmit data information from SSs in reserved slots or minislots. The efficiency of the MAC protocol highly depends on the bandwidth assigned to the contention access. A high number of contention slots (CSs) assigned to this region reduces the bandwidth for data transmission in the reservation region. On the other hand, a small number of contention slots gives rise to an increased number of collisions during high traffic loads, resulting in degradation of system performance.

The IEEE 802.16 MAC protocol specification does not define any mechanism for bandwidth allocation, and this task has been left open to implementations and vendor differentiation.

Recent studies found in the literature focus on system performance related to the support of Quality of Service (QoS) [1-4] and cross-layer issues [5-8] for the IEEE 802.16 MAC protocol. However, few studies [9-11] explicitly approach the analysis of the Best Effort (BE) service class. Performance of the BE service is severely affected as the network gets congested due to collisions of bandwidth requests transmitted on contention slots.

In [9] a performance analysis of the IEEE 802.16 MAC protocol was carried out using three initial backoff windows (BW) of the EBA, $BW_0=[0,2^i-1]$, for i = 0, 4 and 5. Optimum system performance was achieved with i = 4 ($BW_0=[0,15]$). However, the authors in [9] did not consider piggybacking and fragmentation in their analysis, and only two different packet sizes were used. Maximum theoretical system throughput was 77.5% of the channel capacity (*CC*).

In [10] the authors found that optimum system performance can be obtained with $BW_0=[0,K-1]$, and $BW_{max}=[0,2^mK-1]$, where m = t = 4, and K = 6, which represents the minimum number of contention slots per contention period (MCs=K), and t is the truncated value of the EBA. However, the maximum system throughput was considerably reduced to 40% of the *CC*, since again piggybacking and fragmentation were not used.

The authors in [8] and [11] concluded that the optimum system performance is achieved when the contention period (MCs) = number of active subscriber stations (N), using 4 priority classes. In addition, in these performance optimizations, piggybacking and fragmentation mechanisms were not used and the authors also concluded that the maximum system throughput can be up to 75% of the *CC*.

In this paper we propose five Contention Slot Allocators (CSA) for the IEEE 802.16 MAC protocol, which could

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increase considerably the system performance in terms of: mean access delays, mean contention delays and maximum system throughput.

The paper is structured as follows. Section II shows an overview of the IEEE 802.16 standards and a description of the MAC protocol. Section III presents the current CSAs schemes and describes the five CSAs proposed for the IEEE 802.16 MAC protocol. Section IV describes the simulation model used to validate the schemes. In Section V, we present a performance analysis of the current and proposed CSAs for the 802.16 MAC protocol, and then we present our conclusions.

II. IEEE 802.16 MAC PROTOCOL OVERVIEW

A. Standardization process

The IEEE 802.16 group produced a standard that was approved in December 2001 [12]. This standard, Wireless MAN-SC, specified a physical layer that used single-carrier modulation techniques and a media access control (MAC) layer with a burst time division multiplexing (TDM) structure that supported both frequency division duplexing (FDD) and time division duplexing (TDD).

After completing this standard, the group started work on extending and modifying the standard to work in both licensed and license-exempt frequencies in the 2-11 GHz range, which would enable non line of sight (NLOS) deployments. Further revisions to 802.16 were made and completed in 2004. IEEE 802.16-2004 [13] replaces 802.16, 802.16a, and 802.16c with a single standard, which has also been adopted as the basis for HIPERMAN (high-performance metropolitan area network) by ETSI (European Telecommunications Standards Institute).

In 2003, the 802.16 group began work on enhancements of the specifications to allow vehicular applications. That revision, 802.16e, was completed in December 2005 and was published formally as IEEE 802.16e-2005 [14]. It specifies scalable OFDMA (orthogonal frequency division multiple access) for the physical layer and makes further modifications to the MAC layer to accommodate high-speed mobility. In general the three versions use a generalized MAC structure described below.

B. Overview of the MAC Layer

REQ and data from SSs to the BS are carried in an uplink (UL) frame. Transmissions from the BS to SSs are carried by a downlink (DL) frame. A typical signaling frame for TDD includes a UL-frame (see Fig. 1a) and a DL-frame (see Fig. 1b) using a single channel frequency as illustrated in Fig. 1c. In FDD, these frames are transmitted at the same time using different channel frequencies as illustrated in Fig. 1d.

After setup is completed, a SS can create one or more connections over which its data is transmitted to and from the BS. SSs contend for transmission opportunities using the contention access period (or contention block) of the current UL-frame. The BS collects these requests and determines the number of slots (grant size) that each SS will be allowed to transmit in the next UL-frame, using a UL_MAP subframe, as shown in Fig. 1b. The UL-MAP frame contains Information Elements (IE), which describe the maintenance, contention or reservation access of the UL-frame. The UL-MAP is broadcasted in the DL channel by the BS in each DL-Frame.

After receiving the UL-MAP, a SS can transmit data in the predefined reserved slots indicated in the IE. These reserved slots are transmission opportunities assigned by a scheduling algorithm using a QoS Service class, such as UGS (Unsolicited Grant Service) for CBR (Constant Bit Rate) traffic, rtPS (real-time Polling Service) for VBR (Variable Bit Rate), nrtPS (non real-time Polling Service) for non real-time bursty traffic, and BE (Best Effort) for traffic such as Internet, email and all other non real-time traffic. Regarding the UL-frame structure depicted in Fig. 1a, in this work we assume that only contention and reservation slots are considered in the UL-frame, since maintenance slots are included scarcely.

III. ADAPTIVE CONTENTION SLOT ALLOCATORS

In this paper five new adaptive Contention Slot Allocator (CSA) schemes are introduced. These schemes dynamically adjust the number of contention slots per UL-frame according to the current traffic load, mean packet size, mean requested slots and possible collisions. These mechanisms improve the maximum system performance for the EBA by assigning more CSs when they are needed, (and not when they are available) by reducing the average number of CSs needed by a REQ to a value close to the optimum "e = 2.718" as suggested by [15]. We refer to the new mechanisms as: Forced-CSA, Variable-CSA, Multicast-CSA, Collision Free-CSA and CDMA-CSA. In order to demonstrate their superior performance, we also describe the main functionally of previous CSAs, such as Simple-CSA adopted by the IEEE 802.16 MAC protocol and the IEEE 802.14 Variable-CSA as described in [16] for the MAC protocol of the Cable Television System (CATV) IEEE 802.14. We start by describing the current CSAs and then we present our proposed mechanisms.

A) Simple-CSA: This mechanism allocates all slots that are not being used for data as CSs. At low traffic loads, many CSs are allocated but are not required. The surplus of CSs significantly decreases the risk of collision (of bandwidth requests) to a very low level. However on high traffic loads, very

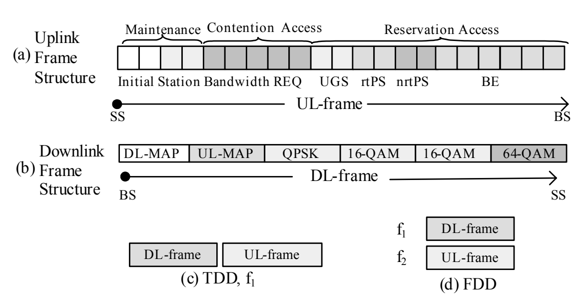

Fig. 1. Frame structure for TDD and FDD access.

few CSs are allocated, thus in order to avoid the high risk of collision, this mechanism guarantees that at least some CSs (termed as *Minimum Contention Slots*-MCs) will be assigned in each contention region of the UL-frame, as illustrated in Fig 2.a. Therefore, the EBA uses the contention access region, formed by MCs and unscheduled slots to resolve collisions.

B) IEEE 802.14-CSA: This mechanism is a variable slot allocation algorithm used for the IEEE 802.14 Cable Television Systems (CATV). The authors in [16] described this mechanism as:

> *"The number of CSs, $N_{CS,}$ contained in each upstream cluster is dynamically adjusted as the headend converts the number of DSs (Data Slots) into CSs, N_{DS}, according to the following expression:*
>
> $$N_{DS} = \left\lceil \frac{2 * MAX\_DATA}{(2 + m * k)} \right\rceil$$
>
> *where MAX_DATA is the maximum of data slots in a frame, m is the number of minislots that a data slot occupies, and k is the average number of DSs that can be requested at a time. As a result, N_{CS} can be determined by:*
>
> $$N_{cs} = \begin{cases} 0 & \text{if } DQ \geq \alpha * (MAX\_DATA - N_{DS}) \\ m * N_{DS} & \text{else} \end{cases}$$
>
> *where DQ is the total number of data slots requested but not yet allocated by the headend, and α is a design parameter set to 2.5."*

In this mechanism, N_{cs} and the unscheduled slots are all used by the EBA to solve current collisions, as indicated in Fig. 2b.

C)Forced-CSA: This mechanism is based on the dynamics of the splitting tree algorithm. When a collision occurs, the splitting tree algorithm automatically allocates three CSs in the next signaling frame, which are then used only by stations involved in the collision. Our proposed mechanism, Forced-CSA, allocates a flexible number of CSs, termed as Forced CSs (FCs) in the next UL-frame for each collision occurred in the current UL-frame, as illustrated in Fig. 2c. However, the MCs, the FCs and the unscheduled slots are all used by the EBA to solve current collisions. In addition, stations competing for contention access for the first time have a better probability of transmitting successfully their bandwidth requests, since more contention slots are allocated in the contention access region. The BS detects a collision when two or more REQ are transmitted in the same contention slot and none of the transmitted REQ can be recovered by the BS.

D) Variable-CSA: This mechanism uses a variable slot regime in which the ratio of CSs to reservations slots is varied from UL-frame to UL-frame based on the current traffic load, current collisions, mean packet size and mean request size. We derived the following procedure to estimate the number of slots that should be converted to contention slots, these slots are called as Variable CSs (VCs):

$if\ Rp > G\ \&\&\ C \leq 2$ //traffic load is high and current collisions are low

$VCs = 0$

$else\ if\ Rp > G\ \&\&\ C > 2\ \&\&\ Rn > 2$ // traffic load and collisions are high

$VCs = \min\{e \cdot C, M_{VCs}\}$

$else$ // traffic load is low

$VCs = M_{VCs}$

where R_p is the number of pending requests at the BS that could not be allocated in the previous UL-frame. R_n is the number of successful REQs that arrived in the current UL-frame, C is the number of collisions in the current UL-frame and e = 2.718. M_{VCs} is a design parameter. G is the number of grants that can be allocated in the next UL-frame, given by the ratio of available slots for transmission of user information (D_s) and the average request size of the previous UL-frames ($\overline{Rs}$), hence

$$G = D_s / \overline{Rs} \tag{1}$$

where D_s is computed as M – MCs, M is the total number of slots per UL-frame. Thus, MCs, VCs and unscheduled slots are all used by the EBA to solve current collisions, as indicated in Fig. 2d.

E) Multicast-CSA: This mechanism allocates a multicast contention region of "m" CSs (mCs) for each collision. The users that provoke a collision in the current UL-frame will have a short reserved contention area in the next UL-frame in order to retransmit their REQ, as illustrated in Fig. 2e. New REQ are not allowed to be transmitted in these multicast contention slots. Here, the backoff window of the EBA for users that incurred in a collision is set to [0, 2^i], were *i* is set to 2, until the collision is solved. Therefore, this mechanism attempts to significantly reduce contention access delays by shortening the reservation region.

This mechanism can be easily implemented in SSs and BS

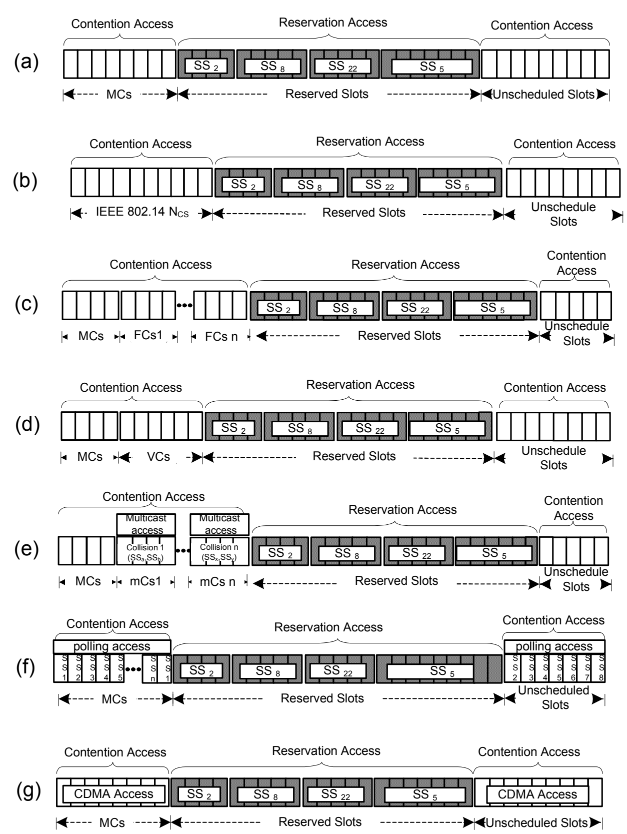

Fig. 2. Uplink frame structure of Contention Slot Allocators. (a) Simple-CSA, (b) IEEE 802.14 Variable-CSA, (c) Forced-CSA, (d) Variable-CSA, (e) Multicast-CSA, (f) Collision Free-CSA and (g) CDMA-CSA.

using the following procedure. When a SS_x sends a REQ for a new packet, SS_x keeps the position of the contention slot used, with reference to the first slot of the current UL-frame, e.g., transmission opportunity no. 5 (SS_x_Topp=5). Then, in case that one or more subscriber stations used the same contention slot than SS_x (e.g. SS_y_Topp=5 an SS_z_Topp =5), the BS will know the position where interference is present, (e.g., Topp=5). Then, this Topp is translated to a multicast CID, as mCID = Topp + iMc, where iMc is a fixed parameter that describes the initial multicast CID for this mechanism, (e.g. iMc=xF000). Thus, the IE that should be included in the next UL-MAP is as follow: IE interval description = Multicast group bandwidth request, IE CID = mCID (e.g. SID =5 + xF00 = 0xF005).

Then, the subscriber stations that provoked the collision will know that their REQ resulted in a collision if no data grant or null grant has been received in the number of subsequent UL-MAP messages specified by the parameter Contention-based reservation timeout (Cbrt), which we have set to 1. The null grant should be transmitted when the BS has received a REQ, but cannot be allocated in the next UL-frame. Thus, SSs that receive no data grant o null grant need to compute the multicast CID, in the same way carried out by the BS, as mCID = Topp + iMc. In case that a SS collides again, (eg. SSx and SSz) they repeat this procedure until the collision is solved.

F) Collision Free-CSA: This scheme assigns a unicast request opportunity to subscriber stations in a Round Robin discipline, as long as space in the current UL-MAP is available. A subscriber station uses its assigned unicast request opportunity to send a REQ, in the same way carried out by the rtPS-scheduling service type. In Collision Free-CSA, the EBA is not utilized since all SSs will receive a unicast transmission opportunity, where the MCs and the unscheduled slots are used for the unicast request opportunities as shown in Fig, 2f.

G) CDMA-CSA: This mechanism assumes that the physical layer includes a second radio with Code Division Multiple Access (CDMA). For the WirelessMAN-OFDM PHY and the WirelessMAN-OFDMA PHY air interfaces, this radio is already included. For WirelessMAN-OFDM PHY, the transmission of REQ is carried out by using the Focused Contention Transmission during a REQ Region Focused, as described in section 6.3.6.4 of IEEE 802.16-2004 [13]. For the WirelessMAN-OFDMA PHY, the transmission of REQ is carried out by using the CDMA-based mechanism as described in section 6.3.6.5 of [13]. However, this radio is not included in WirelessMAN-SCa. Thus, by incorporating a CDMA radio into the WirelessMAN-SCa air interface, SSs can transmit their REQ using a contention code, which is chosen randomly among 8, 64 or 128 codes. In addition, the contention period is fixed to ten slots (MCs=10). We also assume that multiple REQ can be sent in one contention slot by using different contention codes. Thus, the results presented for the CDMA-CSA are carried out with 64 contention codes, where the probability of having a collision

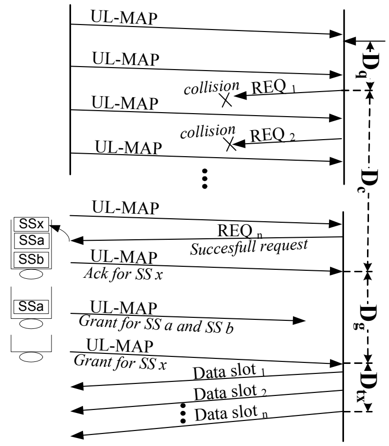

Fig. 3. Access delay components.

is almost zero.

In general, all CSA described above can be modeled by the delay components presented in Fig.3. When a SS is active, (lets say SS_x), it forms a continuous loop with the sequence of actions depicted in Fig. 3. Upon a packet arrival from an upper layer protocol, SS_x waits for the next UL-MAP containing a contention access period, this delay corresponds to the queuing delay (D_q) at SS_x. Then, the SS_x randomly chooses one of the available contention slots, according to the adopted CSA, and transmits a REQ indicating the packet length. In case some other SS (lets say SS_y) selects the same contention slot, a collision occurs and the subscriber stations (SS_x and SS_y) will receive neither a grant nor an acknowledgement (ack) in the following UL-MAP. Thus, SS_x retransmits its REQ until it is successfully received. This delay corresponds to the contention delay (D_c) shown in Fig.3. Upon receiving the REQ from SS_x, the BS converts the packet size to a number of slots that should be reserved in subsequent UL-frames. In case the REQ from SS_x does not fit in the next UL-frame, the BS sends a null grant to SS_x in order to acknowledge the REQ. Thus, the grant delay (D_g) is the time that takes the scheduler at the BS to grant the REQ of SS_x. The last delay component D_{tx} represents the actual time spent during packet transmission from SS_x. Therefore, the mean access delay is formed by the sum of these delay components, $D = D_q + D_c + D_{g+} D_{tx}$. The proposed CSAs will attempt to provide lower contention delays, by maintaining maximum system throughput.

IV. Simulation Model

We implemented a detailed simulation model of the IEEE 802.16 MAC protocol using the OPNET Package v. 14, as described in [4]. A hierarchical design was used and it is shown in Fig. 4. At the top level of the BWA network topology, the network components, for example the BS and SS, along with their connectivity are shown in Fig 4a. The next level, Fig. 4b, defines the functionality of a SS in terms of components such as traffic sources, MAC interfaces, etc. The operation of each component is defined by a state machine (an

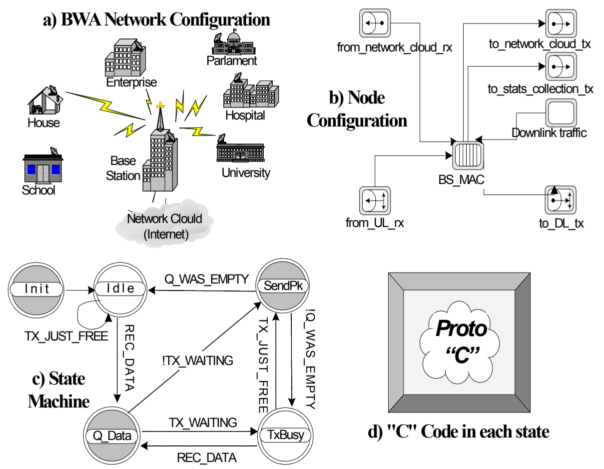

Fig. 4. OPNET simulation model.

example of which is shown in Fig. 4c). The actions of a component at a particular state are defined in Proto-C code such as that in Fig. 4d. This approach allows modifications to be applied to the operation of the IEEE 802.16 protocol and different optimizations and enhancements to be tested.

V. Performance Evaluation

For the system performance, we assume a 6 MHz uplink channel, a roll off factor of 0.25, QPSK modulation, UL bit rate ($UL_{bitrate}$) of 9.6 Mbps. In order to stress the network we assume that SSs transmit Internet traffic, using the packet distribution introduced by the IEEE 802.14 working group [17]: 64-byte packet 60%; 128-byte packet 6%; 256-byte packet 4%; 512-byte packet 2%; 1024-byte packet 25%; and 1518-byte packet 3%. The interarrival times follow a Poisson distribution and the offered load per active station is 38.4 kbps at the PHY layer. The mean packet size at the MAC ($\overline{Pk}_{MAC}$) and PHY ($\overline{Pk}_{PHY}$) layer is of 23 and 26.6 slots respectively. The main configuration parameters used in the performance analysis are given in Table I.

In order to validate the results we estimate the maximum system throughput as

$$S_{\max} = UL_{bitrate} \frac{\overline{Pk}_{MAC}}{\overline{Pk}_{PHY} + CS_{REQ}} \tag{2}$$

where CS_{REQ} is the mean number of contention slots per REQ. When the network is congested (e.g. more than 260 stations) $CS_{REQ} \rightarrow 0$. This is because under high congestion periods most SSs avoid contention access by piggybacking requests in the reservation area. Then, the maximum theoretical system throughput achieved by the network at the MAC layer is $S_{max} = 9600000*(23/26.6) = 8.3$Mbps.

We start by analyzing the system performance of the default CSA of the IEEE 802.16 MAC protocol (Simple-CSA). The results presented in Figs. 5-7 were obtained with the optimized initial and truncated EBA exponents i=3 and t=7 respectively, and considering an optimized contention period,

TABLE 1
SIMULATION PARAMETERS

Parameter	Value
UL Channel Bandwidth/ UL slot size	6 MHz/16 bytes
UL bit rate (QPSK), (=channel capacity)	9.6 Mbps
Slots per UL-Frame (M)	150 slots (≈2ms)
MCs for Simple-CSA, Forced-CSA, Variable-CSA and Multicast-CSA	7
MCs and contention codes for CDMA-CSA	8/64
Interarrival time (1/λ) [s]	Exponential(0.092)
Initial and truncated exponents of EBA used in Simple-CSA, Forced-CSA &Variable-CSA	3,7
Initial and truncated exponents of EBA used in Multicast-CSA	2,2
FCs (Forced-CSA)	3
mCs (Multicast-CSA)	4
Simulation time for each run	60s
Distance from nearest/farthest SS to the BS	0.1 - 5 km

MCs = 7. These exponents were obtained by exhaustive simulation work, where we analyzed the performance of all values of the initial EBA exponent in the set {2,3,5,7}, all values of the truncated EBA exponents in the set {3,5,7,10} and values of MCs in the set {3,5,7,10}.

In Fig.5 we can observe that the Simple-CSA can achieve a system throughput of 8.1 Mbps (84.3% of *CC*), which results in a deviation of approximately 2.2% from the theoretical result, S_{max}=8.3Mbps (86.5% of *CC*). The proposed CSA mechanisms attempt to stay close to S_{max}, while reducing considerably the mean access delays "D". We can observe that the Collision Free-CSA, is the only one that provides a similar system throughput of 8.2Mbps (85.4% of *CC*), achieving a deviation of 1% between theoretical and simulation results. The Multicast-CSA, Forced-CSA and the IEEE 802.14-CSA yielded a similar system throughput of approximately 8 Mbps (3.2% deviation from theoretical S_{max}) and the other two mechanisms CDMA-CSA and Variable-CSA achieved only 7.9 Mbps (4.2% deviation from theoretical S_{max}). For the Multicast-CSA and Forced-CSA this reduction in system throughput is to be expected, since these schemes allocate short contention regions for each collision. By allocating more contention slots when they are needed to solve current collisions, SSs have a better probability of retransmitting REQ successfully, which results in reduced access delays as illustrated in Figs. 6-7. The CDMA-CSA mechanism achieved

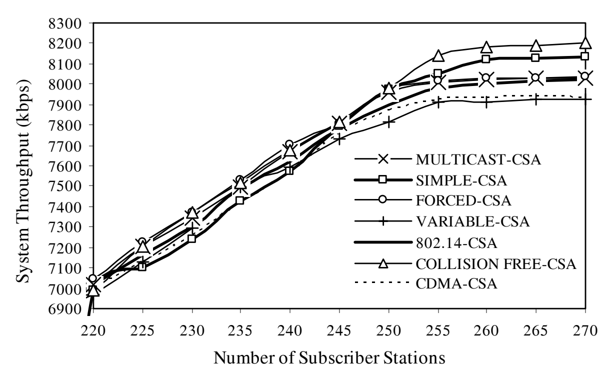

Fig. 5. System Throughput.

lower system throughput due to the large MCs used, which was set to 10 slots, compared with the 7 slots allocated to the other proposed mechanisms.

In Fig. 6 we can observe that the proposed CSA, with the exception of the Variable-CSA, considerably reduce the mean access packet delay compared to the Simple-CSA. This reduction can be up to 75%, 54%, 50% and 33% for the CDMA–CSA, Multicast-CSA, Forced-CSA and Collision Free-CSA, respectively. For the Multicast-CSA and the Forced-CSA this performance is achieved mainly by reducing the collision risk with extra contention slots, which in turn results in lower contention access delays.

In Fig.7 we can observe that contention delays for all CSAs start to decrease when the networks gets saturated. This is a direct consequence of the piggyback mechanism of the IEEE 802.16 MAC protocol, which is used with more frequency by SSs when the network size is larger that 250 SSs. The CDMA–CSA mechanism avoids contention access delay, because requests for bandwidth are transmitted either by the piggyback request mechanism or in the next available contention access period. For the Collision Free-CSA mechanism, the delay presented in Fig.7 corresponds to the polling delay which becomes higher than the contention delay of the Simple-CSA when the network is saturated with more than 250 SSs.

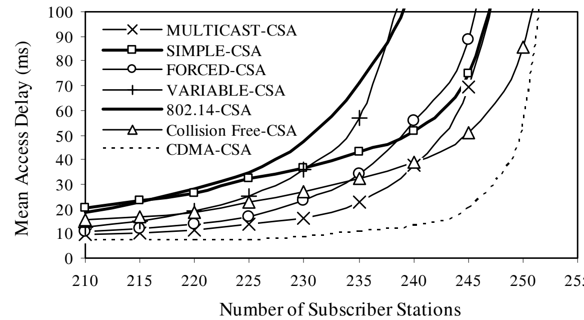

Fig. 6. Mean Access Delay.

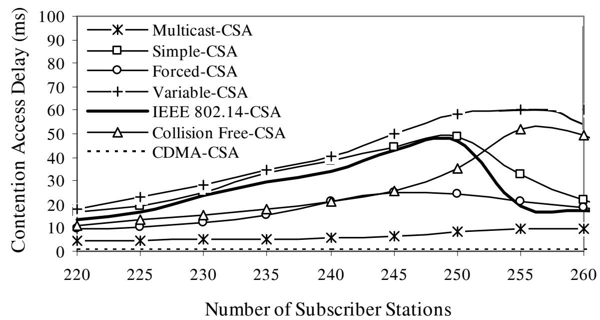

Fig.7. Mean Contention Delay.

VI. CONCLUSIONS

In this paper a performance evaluation of several CSA mechanisms has been presented for the IEEE 802.16 protocol. Simulation results revealed that the system performance could be improved by adopting the proposed mechanisms such as Forced-CSA, Variable-CSA, Multicast-CSA, Collision Free-CSA, and CDMA-CSA. Results measured in simulations agreed well with results from the maximum estimated throughput with a deviation not exceeding 1% for the Collision Free CSA. For the Multicast, Forced-CSA and CDMA-CSA a decrease up to 2% on system throughput was obtained compared to the Simple-CSA, however the performance in terms of access delay was considerably improved. The IEEE 802.14-CSA and the Variable-CSA overestimated the variable contention slots per UL-frame, achieving lower system performance than the optimized Simple-CSA. The Multicast-CSA, Collision Free-CSA, and Forced-CSA can be integrated in the IEEE 802.16 MAC protocol via software with minimal computation requirements for the provision of Best Effort traffic, such as web, telnet, ftp, email among others; however the CDMA-CSA needs a costly multiplexing radio in order to guarantee very low access delays.

REFERENCES

[1] C. Cicconetti, A. Erta, L. Lensini, E. Mingozzi, "Performance Evaluation of the IEEE 802.16 MAC for QoS Support," *IEEE Trans. on Mobile Computing*, vol. 6, no.1, pp. 26-38, Jan. 2007.

[2] R. Iyengar, P. Iyer, B. Sikdar, "Delay Analysis of 802.16 based Last Mile Wireless Networks," in *2005 Proc. GLOBECOM Conf.*, St. Louis.

[3] Y. Yu, H. Chao, "QoS Aware Link Adaptation in IEEE 802.16 Broadband Wireless Access Systems," in *2007 Proc. PIMRC Conf.*

[4] V. Rangel, J. Gómez, J. Ortiz, "Performance Analysis of QoS Scheduling in Broadband IEEE 802.16 Based Networks," *in Proc. of OPNETWORK Technology Conf.*, Washington, August, 2006.

[5] D.Hao, S.Zou, B. Adamou, "A QoS Guaranteed Cross-Layer Scheduling Algorithm in Wireless Networks," in *2003 Proc. ICWMC Conf.*

[6] J. Yan, G. Kuo, "Cross-Layer Design of Optimal Contention Period for IEEE 802.16 BWA Systems," in *Proc. IEEE ICC 2006*, Istanbul.

[7] Y. Chang, F. Chien, J. Kuo, "Cross-Layer QoS Analysis of Opportunistic OFDM-TDMA and OFDMA Networks," *IEEE Journal of Selected Areas in Communications*, vol. 25, no. 4, May 2007.

[8] Y. Mai, C. Yang, Y. Lin, "Cross-Layer QoS Framework in the IEEE 802.16 Networks," in *Proc. ICACT 2007*, Gangwon-Do, Korea

[9] B. Bhandari, R. Kumar, S. Maskara, "Performance of the IEEE 802.16 MAC Protocol with Varying Request Backoff Start," in *Proc. IEEE TENCON 2006*, Hong Kong.

[10] A. Vinel, Y. Zhang, M. Lott, A. Tiurlikov, "Performance Analysis of the Random Access in IEEE 802.16," *in Proc. IEEE PIMRC 2005*", Berlin.

[11] D. Cho, J. Song, M. Kim, K. Han, "Performance Analysis of the IEEE 802.16 Wireless Metropolitan Area Networks," *in Proc. of OFMA 2005*, Besançon, France.

[12] IEEE 802.16-2001, "IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air Interface for Fixed Broadband Wireless Access Systems," April 2002.

[13] IEEE 802.16-2004, "IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air Interface for Fixed Broadband Wireless Access Systems," October 2004.

[14] IEEE 802.16e, "IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air Interface for Fixed BWA Systems", Amendment for PHY and MAC for Combined Fixed and Mobile Operation in Licensed Bands," IEEE 802.16 Working Group, December 2005.

[15] D. Bertsekas, R. Gallager, *Data Networks*, Englewood Cliffs, NJ, Prentice-Hall, Second edition. pp 271-362, 1992.

[16] N. Golmie, Y. Saintillan, D. Su, "A Review of Contention Resolution Algorithms for IEEE 802.14 Networks", *IEEE Communication Surveys*, Vol. 2, No. 1, 1999.

[17] IEEE 802.14, "IEEE 802.14 Broadband CATV Protocol, Draft 3, Release 3", *IEEE 802.14 Subcommittee*, November 1998.